

TeV-scale seesaw from a multi-Higgs model

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Abstract

We suggest new simple model of generating tiny neutrino masses through a TeV-scale seesaw mechanism without requiring tiny Yukawa couplings. This model is a simple extension of the standard model by introducing extra one Higgs singlet, and one Higgs doublet with a tiny vacuum expectation value. Experimental constraints, electroweak precision data and no large flavor changing neutral currents, are satisfied since the extra doublet only has a Yukawa interaction with lepton doublets and right-handed neutrinos, and their masses are heavy of order a TeV-scale. Since active light neutrinos are Majorana particles, this model predicts a neutrinoless double beta decay.

1 Introduction

The recent neutrino oscillation experiments gradually reveal a structure of lepton sector[1, 2]. However, from the theoretical point of view, smallness of neutrino mass is still a mystery and it is one of the most important clues to find new physics beyond the standard model (SM). Seesaw mechanism naturally realizes tiny masses of active neutrinos through heavy particles coupled with left-handed neutrinos. In usual type I seesaw[3], tiny neutrino masses of order 0.1 eV implies an existence of right-handed neutrinos with super-heavy Majorana masses, which are almost decoupled in the low-energy effective theory, and then few observations are expected in collider experiments. Some people consider a possibility of reduction of seesaw scale to TeV, where effects of TeV-scale right-handed neutrinos might be observed in collider experiments such as LHC and ILC[4, 5]. However, they must introduce a fine-tuning in order to realize both tiny neutrino mass and detection of the evidence of right-handed neutrinos from a mixing with the SM particles.

How about considering a possibility that smallness of the neutrino masses comparing to those of quarks and charged leptons is originating from an extra Higgs doublet with a tiny vacuum expectation value (VEV) of order 0.1 eV. It is an idea that neutrino masses are much smaller than other fermions since the origin of them comes from different VEV of different Higgs doublet, and where tiny neutrino Yukawa couplings are not required. This kind of model has been considered in Dirac neutrino case[6, 7, 8].

In this paper, we would like to propose a simple model for Majorana neutrino case, which is a renormalizable model with minimal extension of the SM which appears entirely below the TeV-scale. A similar setup was proposed firstly in Ref.[9], where a global $U(1)$ lepton number symmetry is violated explicitly. Tiny Majorana neutrino masses are obtained through a TeV-scale type I seesaw mechanism without requiring tiny Yukawa couplings. This model contains extra one Higgs singlet, and one Higgs doublet with a tiny VEV. As for extending a Higgs sector, there are constraints in general, which are consistency of electroweak precision data* and absence of large flavor changing neutral currents (FCNCs)[10]. In our model, both two constraints are satisfied since the extra doublet only has a Yukawa interaction with lepton doublets and right-handed neutrinos[†], and their masses are heavy enough to suppress FCNCs although its VEV is of order 0.1 eV. The extra Higgs doublet yields a neutral scalar and a neutral pseudo-scalar, and a charged Higgs particles, which can provide collider signatures. This charged Higgs can contribute to the lepton flavor violating processes. The extra singlet produces TeV-scale Majorana masses of right-handed neutrinos, and yields a neutral scalar and a neutral pseudo-scalar with a lepton number. Other phenomenology will be also represented

* It is pointed out that the second Higgs doublet heavier than SM-like Higgs can potentially make the precision electroweak data be consistent[11].

[†] This is a kind of a “leptonic Higgs” which could explain PAMERA and ATIC results[12].

such as the charged Higgs decay processes. Notice that the decay of the charged Higgs to quarks and charged leptons are strongly suppressed due to absence of direct interactions among them, which is one of different points from usual two Higgs double models. Since active light neutrinos are Majorana particles, this model predicts a neutrinoless double beta decay.

This paper is organized as follows. In section 2, we show a setup of this model, and analyze its vacuum and mass spectra. In section 3, we discuss some phenomenology's. Finally, we summarize our conclusions.

2 A Model

2.1 Lagrangian and vacuum

In our model, we introduce one doublets Higgs H_ν and one singlet Higgs S , which has a lepton number and couples with right-handed neutrinos, in addition to the SM. The SM Higgs doublet H and new Higgs double H_ν are denoted as

$$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}, \quad H_\nu = \begin{pmatrix} H_\nu^0 \\ H_\nu^- \end{pmatrix}. \quad (2.1)$$

We introduce Z_3 -symmetry, whose charges (and also lepton number) are shown as the following table.

fields	Z_3 -charge	lepton number
SM Higgs doublet, H	1	0
new Higgs doublet, H_ν , which couples with N	ω^2	0
new Higgs singlet, S , which has a lepton number	ω	-2
Right-handed neutrinos, N	ω	1
Others	1	1: leptons, 0: quarks

Under the discrete symmetry, Yukawa interactions are given by

$$\mathcal{L}_{yukawa} = y^u \bar{Q}_L H U_R + y^d \bar{Q}_L \tilde{H} D_R + y^l \bar{L} \tilde{H} E_R + y^\nu \bar{L} H_\nu N + \frac{1}{2} y^N S \bar{N}^c N + \text{h.c.} \quad (2.2)$$

where $\tilde{H} = i\sigma_2 H^*$. We omit a generation index here.

Through the interactions of $y^\nu \bar{L} H_\nu N + \frac{1}{2} y^N S \bar{N}^c N$ with VEVs of H_ν and S as $\langle H_\nu \rangle \ll \langle H \rangle \ll \langle S \rangle$,

$$\langle S \rangle \sim 1 \text{ TeV}, \quad \langle H \rangle \sim 100 \text{ GeV}, \quad \langle H_\nu \rangle \sim 10^{-0.5} \text{ MeV}, \quad (2.3)$$

neutrino mass is generated as

$$m_\nu \bar{\nu}_L^c \nu_L \simeq \frac{y^{\nu^2} \langle H_\nu \rangle^2}{y_N \langle S \rangle} \bar{\nu}_L^c \nu_L. \quad (2.4)$$

This is so-called type-I seesaw mechanism in a TeV-scale, where coefficients y^ν and y^N are assumed to be of order one. Notice that the suitable scale of tiny neutrino mass of $O(0.1)$ eV is obtained.

As for Higgs potential, it is given by

$$\begin{aligned} V = & m^2 |H|^2 + m_1^2 |H_\nu|^2 - M^2 |S|^2 - m_{12}^2 H^\dagger H_\nu - \lambda S^3 - \mu S H^\dagger H_\nu \\ & + \frac{\lambda_1}{2} |H|^4 + \frac{\lambda_2}{2} |H_\nu|^4 + \lambda_3 |H|^2 |H_\nu|^2 + \lambda_4 |H^\dagger H_\nu|^2 \\ & + \lambda_S |S|^4 + \lambda_H |S|^2 |H|^2 + \lambda_{H_\nu} |S|^2 |H_\nu|^2 + h.c.. \end{aligned} \quad (2.5)$$

It should be noted that interactions, such as $(H^\dagger H_\nu)^2$, $H^\dagger H_\nu |H|^2$, $H^\dagger H_\nu |H_\nu|^2$, S^4 , $S^2 |H|^2$, $S^2 |H_\nu|^2$, etc, are forbidden by Z_3 -symmetry. The lepton number symmetry $U(1)_L$, it is softly broken by both λ and μ terms. Here we neglect mass term of S^2 ($\leq O(1)$ TeV), for simplicity, since the following analyses do not change as long as we do not consider larger than $O(1)$ TeV-mass of S^2 nor CP violation in the Higgs sector. The mass term of $m_{12}^2 H^\dagger H_\nu$, which softly breaks Z_3 -symmetry, is introduced to avoid domain-wall problem. Here $|m_{12}^2|$ is assumed to be smaller than $|\mu \langle S \rangle|$ (it means $m_{12}^2 \leq 10^{0.5}$ GeV in the following analyses),[‡] and this smallness (comparing to the weak scale) against radiative corrections is guaranteed by the *softly breaking* Z_3 -symmetry. Other soft breaking Z_3 -symmetry terms, such as $\mu' S |H|^2$, are dropped, for simplicity, since the following analyses are not changed as long as $|\mu' \langle S \rangle| \leq |m^2|$.

By denoting VEVs as[§]

$$\langle S \rangle = s, \quad \langle H \rangle = \begin{pmatrix} h \\ 0 \end{pmatrix}, \quad \langle H_\nu \rangle = \begin{pmatrix} h_\nu \\ 0 \end{pmatrix}, \quad (2.6)$$

stationary conditions

$$\frac{\partial V}{\partial s} = 0, \quad \frac{\partial V}{\partial h} = 0, \quad \frac{\partial V}{\partial h_\nu} = 0, \quad (2.7)$$

induce following equations,

$$-2M^2 s - 6\lambda s^2 - 2\mu h h_\nu + 4\lambda_S s^3 + 2\lambda_H h^2 s + 2\lambda_{H_\nu} h_\nu^2 s = 0, \quad (2.8)$$

$$2m^2 h - 2\mu s h_\nu + 2\lambda_1 h^3 + 2\lambda_3 h h_\nu^2 + 2\lambda_4 h h_\nu^2 + 2\lambda_H h s^2 - 2m_{12}^2 h_\nu = 0, \quad (2.9)$$

$$2m_1^2 h_\nu - 2\mu s h + 2\lambda_2 h_\nu^3 + 2\lambda_3 h^2 h_\nu + 2\lambda_4 h^2 h_\nu + 2\lambda_{H_\nu} h_\nu s^2 - 2m_{12}^2 h = 0, \quad (2.10)$$

[‡] To obtain the desirable VEV-hierarchy of Eq.(2.18) from a stationary condition of Eq.(2.17), a condition $|m_{12}^2| < \frac{|\lambda_3 \langle H_\nu \rangle \langle S \rangle^2|}{|\langle H \rangle|}$ should be needed, which is automatically satisfied under the condition of $|m_{12}^2| < |\mu \langle S \rangle|$.

[§] Here we assume the VEVs for real. Case of complex VEVs can be analyzed similarly.

respectively. Let us show conditions for the desirable vacuum, $h_\nu \lll h \ll s$. The hierarchy of VEVs reduces Eq.(2.8) to

$$-2M^2s - 6\lambda s^2 + 4\lambda_S s^3 = 0, \quad (2.11)$$

which means

$$s = \frac{M'}{\sqrt{2\lambda_S}} \quad (2.12)$$

where $M' = \delta + \sqrt{M^2 + \delta^2}$ and $\delta = \sqrt{\frac{9\lambda^2}{8\lambda_S}}$. The value of δ is small of order $10^{0.5}$ MeV as a scale of soft breaking of the lepton number symmetry, which should be the same scale as μ as shown later.

As for Eq.(2.9), the hierarchy of VEVs reduces the stationary condition as

$$2(\lambda_H s^2 + m^2)h - 2\mu s h_\nu + 2\lambda_1 h^3 = 0. \quad (2.13)$$

When

$$\mu s h_\nu \ll \lambda_1 h^3, \quad (2.14)$$

we can neglect $\mu s h_\nu$ -term, and VEV of the SM-like Higgs becomes

$$h = \frac{m'}{\sqrt{\lambda_1}}, \quad (2.15)$$

where positive parameter m' is defined as

$$m'^2 = -\lambda_H s^2 - m^2. \quad (2.16)$$

In the SM, m^2 must be negative for so-called wine-bottle-type potential. However, this model does not require negative mass squared of $m^2 < 0$, since the *effective negative mass squared* of $m'^2 (= -\lambda_H s^2 - m^2) > 0$ can be achieved with a negative λ_H . The negative λ_H does not break potential conditions of bounded below, as long as the value of $|\lambda_H|$ is smaller than values of other four-point couplings, λ s, as shown in Appendix A. So, one option is to take $\lambda_1 \sim 1$ and $\lambda_H \sim -0.01$ which induces $m'^2 \sim \mathcal{O}(100^2)$ GeV², and then the suitable scale of $\langle H \rangle \sim 100$ GeV is realized through Eq.(2.18) and $\langle S \rangle \sim 1$ TeV.

Finally, the third stationary condition of Eq.(2.10) with the VEV-hierarchy becomes

$$-2\mu s h + 2\lambda_{H_\nu} h_\nu s^2 - 2m_{12}^2 h = 0. \quad (2.17)$$

Considering enough small Z_3 -symmetry breaking mass m_{12} ,[¶] we obtain the VEV of H_ν as

$$h_\nu = \frac{\mu h}{\lambda_{H_\nu} s}. \quad (2.18)$$

[¶]This is the condition already shown in the second previous footnote.

When we take $\mu \sim 10^{0.5}$ MeV, the desirable magnitude of VEVs in Eq.(2.3) are reproduced, which is consistent with Eq.(2.14). Since μ is soft breaking mass of the lepton number symmetry, its smallness is guaranteed against from radiative corrections. Anyhow, notice that the small magnitude of three-point mass parameter, μ , plays a crucial role for generating suitable magnitude of neutrino masses.

2.2 Higgs mass spectra

In a previous subsection, we can obtain tiny VEV of extra Higgs doublet which is suitable for the magnitude of neutrino masses through the seesaw mechanism. This is a nice feature, but do any light physical Higgs particles appear due to the tiny VEV? Here, in this subsection, we estimate mass spectra of physical Higgs bosons.

Denoting

$$\begin{aligned} S &= s + \text{Re}S + i\text{Im}S, \\ H &= \begin{pmatrix} h + \text{Re}H^0 + i\text{Im}H^0 \\ H^- \end{pmatrix}, \quad H_\nu = \begin{pmatrix} h_\nu + \text{Re}H_1^0 + i\text{Im}H_\nu^0 \\ H_\nu^- \end{pmatrix}, \end{aligned} \quad (2.19)$$

a component of Higgs mass matrix is given by

$$M_{ij}^2 = \frac{1}{2} \frac{\partial^2 V}{\partial v_i \partial v_j} \quad (2.20)$$

where v_i means s, h, h_ν . Here, the Higgs sector does not have CP violation, so that 6×6 neutral Higgs mass matrix is given by

$$M_{Higgs}^2 = \begin{pmatrix} M_{even}^2 & 0 \\ 0 & M_{odd}^2 \end{pmatrix}, \quad (2.21)$$

with

$$\begin{aligned} M_{even}^2 &= \begin{pmatrix} -3\lambda s + 4\lambda_S s^2 + \frac{\mu h h_\nu}{s} & -2\lambda_H h s - h_\nu \mu & 2\lambda_{H_\nu} h_\nu s - h\mu \\ -2\lambda_H h s - h_\nu \mu & 2\lambda_1 h^2 + (m_{12}^2 + s\mu) \frac{h_\nu}{h} & 2\lambda_3 h h_\nu + 2\lambda_4 h h_\nu - m_{12}^2 - s\mu \\ 2\lambda_{H_\nu} h_\nu s - h\mu & 2\lambda_3 h h_\nu + 2\lambda_4 h h_\nu - m_{12}^2 - s\mu & 2\lambda_2 h_\nu^2 + (m_{12}^2 + s\mu) \frac{h}{h_\nu} \end{pmatrix}, \\ M_{odd}^2 &= \begin{pmatrix} 9\lambda s + \frac{\mu h h_\nu}{s} & -h_\nu \mu & h\mu \\ -h_\nu \mu & (m_{12}^2 + s\mu) \frac{h_\nu}{h} & -m_{12}^2 - s\mu \\ h\mu & -m_{12}^2 - s\mu & (m_{12}^2 + s\mu) \frac{h}{h_\nu} \end{pmatrix}. \end{aligned}$$

For the CP even sector, three physical (mass eigenstates) Higgs scalars are denoted as

$$\begin{pmatrix} H_S \\ h_0 \\ H_0 \end{pmatrix} = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -s_1 c_3 + c_1 s_2 s_3 & c_1 c_3 + s_1 s_2 s_3 & -c_2 s_3 \\ -s_1 s_3 - c_1 s_2 c_3 & c_1 s_3 - s_1 s_2 c_3 & c_2 c_3 \end{pmatrix}^\dagger \begin{pmatrix} \text{Re } S \\ \text{Re } H \\ \text{Re } H_\nu \end{pmatrix}, \quad (2.22)$$

where $c_i = \cos \alpha_i$, $s_i = \sin \alpha_i$ with

$$\alpha_1 = -\frac{2\lambda_H s h}{m_{H_S}^2 - m_{h_0}^2} \quad \alpha_2 = \frac{2\lambda_{H_\nu} s h_\nu - \mu h}{m_{H_S}^2 - m_{H_0}^2} \quad \alpha_3 = \frac{2(\lambda_3 + \lambda_4) h h_\nu - m_{12}^2 - \mu s}{m_{H_0}^2 - m_{h_0}^2}. \quad (2.23)$$

The scalar masses are given by

$$m_{H_S}^2 = M^2 + 2\lambda_S s^2, \quad m_{h_0}^2 = 2\lambda_1 h^2, \quad m_{H_0}^2 = (m_{12}^2 + \mu s) \frac{h}{h_\nu}. \quad (2.24)$$

Under the condition of $h_\nu \lll h \ll s$, we know that SM-like Higgs, h_0 , is composed mainly of H and small components of $a_1(h/s)S + a_2(h_\nu/h)H_\nu$, where a_i s are order one coefficients. Similarly, H_0 is composed of $\sim H_\nu + a_3(h_\nu/h)H + a_4(h_\nu/s)S$ and H_S is composed of $\sim H_S + a_5(h/s)H + a_6(h_\nu/s)H_\nu$.

Next, CP odd Higgs sector has two Higgs pseudo-scalar, and one would-be NG boson which is absorbed into Z -boson. Two (mass eigenstates) pseudo-scalars and would-be NG boson are denoted as

$$\begin{pmatrix} A_S \\ \chi_0 \\ A_0 \end{pmatrix} = \begin{pmatrix} c'_2 & 0 & s'_2 \\ 0 & c'_3 & -c'_2 s'_3 \\ -s'_2 c'_3 & +s'_3 & c'_2 c'_3 \end{pmatrix}^\dagger \begin{pmatrix} \text{Im} S \\ \text{Im} H \\ \text{Im} H_\nu \end{pmatrix} \quad (2.25)$$

where $c'_i = \cos \beta_i$, $s'_i = \sin \beta_i$. Mixing angles are given by

$$\tan \beta_2 = \frac{\xi' - \sqrt{\xi'^2 + \eta'^2 + \eta_1'^2}}{\xi' + \sqrt{\xi'^2 + \eta'^2 + \eta_1'^2}}, \quad \tan \beta_3 = \frac{h_\nu}{h}, \quad (2.26)$$

where $\xi = \frac{p}{q}$, $\eta_1 = \frac{h}{q}$, $\eta_2 = \frac{h_\nu}{q}$, $\xi' = \frac{p}{q'}$, $\eta_1' = \frac{h}{q'}$, $\eta_2' = \frac{h_\nu}{q'}$, $p = \frac{9\lambda s^2 + \mu h h_\nu}{2\mu s} - \frac{m_{12}^2 + \mu s}{2\mu h_\nu} h$, $q^2 = (p + \sqrt{p^2 + h^2 + h_\nu^2})^2 + h^2 + h_\nu^2$, $q'^2 = (p - \sqrt{p^2 + h^2 + h_\nu^2})^2 + h^2 + h_\nu^2$. Under the condition of $h_\nu \lll h \ll s$, two pseudo-Higgs bosons are given by

$$A_S \sim \text{Im} S, \quad A_0 \simeq \text{Im} H_\nu, \quad (2.27)$$

which means A_0 (A_S) is composed mainly of H_ν (S). These masses are given by

$$m_{A_S}^2 = 9\lambda s, \quad m_{A_0}^2 = (m_{12}^2 + \mu s) \frac{h}{h_\nu}. \quad (2.28)$$

They are proportional to the *soft breaking* mass parameters, λ and μ , since they are NG bosons of global $U(1)$ symmetries. It should be noticed that A_0 has the same as H_0 . Supposing $\lambda = 0$ and $m_{12}^2 = 0$, Lagrangian has an accidental global symmetry,

$$H \rightarrow e^{-i\theta_1} H, \quad H_\nu \rightarrow e^{i\theta_1} H_\nu, \quad S \rightarrow e^{-i2\theta_1} S. \quad (2.29)$$

Then massless NG boson appears after the symmetry breaking caused by VEVs of Higgs fields. Similarly, when $\mu = 0$ and $m_{12}^2 = 0$, there exists a global symmetry,

$$H \rightarrow e^{i\theta_2} H, \quad H_\nu \rightarrow e^{-i\theta_2} H_\nu, \quad (2.30)$$

which induces a massless NG boson after the symmetry breaking. These mass parameters λ and μ also break lepton number symmetry, so that the pseudo-scalars can be regarded as so-called “Majoron”. But they are heavier than the SM-like Higgs as long as $\lambda \geq \mathcal{O}(10)$ GeV.

As for the charged Higgs sector, would-be NG boson, χ^+ , and physical state, h^+ , are given by

$$\chi^+ = \cos \beta_3 H^+ - \sin \beta_3 H_\nu^+, \quad h^+ = \sin \beta_3 H^+ + \cos \beta_3 H_\nu^+. \quad (2.31)$$

The charged Higgs mass is given by

$$m_{h^+}^2 = -\lambda_4(h^2 + h_\nu^2) + \frac{2(m_{12}^2 + \mu s)}{\sin 2\beta_3}. \quad (2.32)$$

Note that the second term is almost same as the masses of H_0 and A_0 due to $h/h_\nu \gg 1$, and the mass difference between $m_{h^\pm}^2$ and $m_{H_0}^2, m_{A_0}^2$ is just a weak scale squared from the first term. Charged Higgs plays crucial roles of phenomenology, such as lepton flavor violating processes. We show some phenomenology induced from the charged Higgs boson in the next section.

Before ending of this section, we comment on limits of $h/s \rightarrow 0$ and $h_\nu/h \rightarrow 0$. In the limits, the SM-like Higgs is just H and its physical state is physical neutral Higgs, h_0 , and an imaginary part and charged components are absorbed by Z and W^\pm . As for a singlet Higgs, S , and an extra doublet Higgs, H_ν , they are origins of other physical Higgs particles, H_S, A_S , and H_0, A_0, h^\pm , respectively. Notice that these approximations are justified up to ratios of VEVs.

3 Phenomenology

This section is devoted to some phenomenology of our model. We show decay of Higgs bosons, lepton flavor violation process, ρ parameter, neutrinoless double beta decay, and so on.

3.1 Decay of charged-Higgs boson

Since the charged Higgs mass is given by Eq.(2.32), it becomes smaller or larger than masses of H_0, A_0 depending on a sign of λ_4 . There is also a possibility that the charged Higgs mass is smaller or larger than masses of right-handed neutrinos. Thus, a dominant process of charged Higgs decay depends on the mass spectra of them. We will show four cases according to $m_{h^\pm} < m_{H_0, A_0}$ or $m_{h^\pm} > m_{H_0, A_0}$ and $m_{h^\pm} < m_N$ or $m_{h^\pm} > m_N$, as follows. A important point is that the decay of charged Higgs to quarks and charged leptons are strongly suppressed due to the absence of direct couplings among them, which is one of the different points from the usual two Higgs double models.

3.1.1 $m_{h^\pm} < m_{H_0, A_0}, m_N$

At first, let us show the case of $m_{h^\pm} < m_{H_0, A_0}, m_N$. In this case, only possible charged Higgs decay modes are to quarks and charged leptons through the Yukawa interactions of Eq.(2.2). Since the charged Higgs is mainly composed by H_ν , its coupling with quarks and charged leptons are always suppressed by $\sim h_\nu/h$. Thus, this case tends to induce long life time of charged Higgs comparing to cases of other mass spectra. The effective Yukawa interactions between h^+ and quarks and charged leptons are given by

$$L_{yukawa} = (y_{ij}^d h^+ \bar{u}_{L_i} d_{R_j} + y_{ij}^u h^+ \bar{d}_{L_i} u_{R_j} + y_{ij}^l h^+ \bar{\nu}_i l_{R_j}) \sin \beta_3 + y_{ij}^N h^+ \bar{l}_{L_i} N_j \cos \beta_3 \quad (3.33)$$

Then, the total decay width is given by

$$\begin{aligned} \Gamma_{tot} &= \Gamma(h^+ \rightarrow u_{L_i} \bar{d}_{R_j}) + \Gamma(h^+ \rightarrow \bar{d}_{L_i} u_{R_j}) + \Gamma(h^+ \rightarrow \nu_i \bar{l}_{R_j}) \\ &= \sum_{i,j} \frac{3m_{h^+}}{16\pi} \sin^2 \beta_3 (|y_{ij}^d|^2 + |y_{ij}^u|^2 + \frac{1}{6}|y_{ij}^l|^2). \end{aligned} \quad (3.34)$$

It means the charged Higgs almost decays to right-handed top and left-handed bottom quarks due to the large Yukawa coupling. Using $\sin \beta_3 \simeq h_\nu/h$, the life time of charged Higgs is given by

$$\tau(h^\pm) \sim 10^{-16} s. \quad (3.35)$$

It means the charged Higgs propagates a very short distance which can not be detected in the detector of collider experiments.

3.1.2 $m_N < m_{h^\pm} < m_{H_0, A_0}$

Next, we show the case of $m_N < m_{h^\pm} < m_{H_0, A_0}$. In this case, the charged Higgs can decay to (left-handed) charged leptons and right-handed neutrinos through the Yukawa interaction of $y^\nu \bar{L} H_\nu N$ in Eq.(3.33), which has no suppression factor because of $\cos \beta_3 \simeq 1$. Then, the decay width is given by

$$\Gamma(h^+ \rightarrow N_i l_{L_j}) = \frac{m_{h^+}}{32\pi} |y_{ij}^\nu|^2 \left(1 - \frac{m_{N_i}^2}{m_{h^+}^2}\right). \quad (3.36)$$

Remind that in the usual two Higgs doublet model, the charged Higgs mainly decay to the heavy quarks. While, in our model with this mass spectrum, the charged Higgs mainly decays to charged leptons and right-handed neutrinos. When the right-handed neutrinos are missing in the collider experiments, this is a single charged lepton event with missing transverse momentum, which can be clearly detected in the detector. Especially, the case that y^ν of the first and second generations are larger than that of the third generation is interesting, which induces electron and muon events in collider experiments, and they can be clearly detected.

This situation can be consistent with any neutrino mass hierarchies through the seesaw mechanism with a suitable mass hierarchy of right-handed neutrinos. Notice that this situation can not be realized in case of Dirac neutrino scenario[9, 6, 7, 8].

3.1.3 $m_{H_0, A_0} < m_{h^\pm} < m_N$

Next is devoted to the case of $m_{H_0, A_0} < m_{h^\pm} < m_N$. The dominant charged Higgs decay mode is $h^\pm \rightarrow W^\pm H_0, A_0$ through the gauge interaction. The decay width is given by

$$\Gamma(h^+ \rightarrow W^+ H_0, A_0) \simeq \frac{g_2^2 m_{h^+}^3}{16\pi m_W^2} \left(1 - \frac{m_{H_0, A_0}^2}{m_{h^+}^2}\right)^3, \quad (3.37)$$

where g_2 is the gauge coupling of weak interaction. Notice that the decay processes to quarks and charged leptons are strongly suppressed due to the suppression factor, $\sin \beta_3 \simeq h_\nu/h$, as Eq.(3.34). This is one of the different points from the usual two Higgs double models where the main decay mode is heavy quarks.

3.1.4 $m_{h^\pm} > m_{H_0, A_0}, m_N$

Finally, let us show the case of $m_{h^\pm} > m_{H_0, A_0}, m_N$. In this case, the charged Higgs h^+ can decay both to $W^+ H_0, A_0$ and $N_i l_{L_j}$. They have no suppression factor from h_ν/h , so that each decay width is given by

$$\Gamma(h^+ \rightarrow W^+ H_0, A_0) \simeq \frac{g_2^2 m_{h^+}^3}{16\pi m_W^2} \left(1 - \frac{m_{H_0, A_0}^2}{m_{h^+}^2}\right)^3, \quad (3.38)$$

$$\Gamma(h^+ \rightarrow N_i l_{L_j}) = \frac{m_{h^+}}{32\pi} |y_{ij}^\nu|^2 \left(1 - \frac{m_{N_i}^2}{m_{h^+}^2}\right). \quad (3.39)$$

The dominant decay mode depends on the magnitude of $|y^\nu|$ and degeneracy factor of m_h^\pm and m_{H_0, A_0}, m_N . Thus, the main mode can not be determined until a concrete mass spectrum is fixed. One interesting example is a case of $m_{h^\pm} \geq m_{H_0, A_0} > m_N$. Taking $y^\nu \sim 1$ for the heaviest neutrino and degenerate right-handed Majorana masses, and also considering mass hierarchy of active neutrinos, inverted (normal) hierarchy, IH (NH), induces single left-handed muon (tau) event with missing transverse momentum as a dominant decay mode.^{||}

3.2 ρ parameter

Next, let us estimate charged Higgs contribution to ρ parameter, which is almost same as usual two Higgs doublet models[10] due to the small mixings between the singlet Higgs S and

^{||} Notice that this is quite different point from the usual two Higgs doublet models.

Higgs doublets H, H_ν . It is estimated as

$$\delta\rho = \sqrt{2}G_F \frac{1}{(4\pi)^2} \left[F_\Delta(m_{A_0}^2, m_{h^\pm}^2) - s_{\alpha-\beta}^2 [F_\Delta(m_{h_0}^2, m_{A_0}^2) - F_\Delta(m_{h_0}^2, m_{h^\pm}^2)] \right. \\ \left. - c_{\alpha-\beta}^2 [F_\Delta(m_{H_0}^2, m_{A_0}^2) - F_\Delta(m_{H_0}^2, m_{h^\pm}^2)] \right], \quad (3.40)$$

where $c_{\alpha-\beta} = \cos(\alpha_3 - \beta_3)$, $s_{\alpha-\beta} = \sin(\alpha_3 - \beta_3)$, and

$$F_\Delta(x, y) = \frac{1}{2}(x + y) - \frac{xy}{x - y} \ln \frac{x}{y}. \quad (3.41)$$

The α_3 represents (almost) mixing angle between h_0 and H_0 , and h_0 is almost SM-like Higgs since $c_{\alpha-\beta} \simeq 1$. The mass spectrum shows h^\pm and A_0 are degenerate in TeV-scale as $\left| \frac{m_{h^\pm}^2 - m_{A_0}^2}{m_{h^\pm}^2} \right| = \left| \frac{h^2}{m_{h^\pm}^2} \right| \sim 0.01$. Thus, $\delta\rho$ is estimated as

$$\delta\rho_{2HDM} \simeq \frac{2\sqrt{2}G_F}{(4\pi)^2} F_\Delta(m_{A_0}^2, m_{h^\pm}^2) \simeq \frac{\sqrt{2}G_F}{3(4\pi)^2} \frac{\lambda_4 h^2}{m_{h^\pm}} \sim 10^{-7}, \quad (3.42)$$

which means the correction to ρ parameter is negligible in our model.

3.3 Decay of h_0

Here we show a decay of SM-like Higgs h_0 , which has tiny coupling with neutrinos due to the small mixing $\sim \sin \alpha_3$. In our setup, Higgs mass spectrum is given by $m_{h_0} < 2m_{h^\pm, H_0, A_0, H_S, A_S}$, so that the SM-like Higgs h_0 decay to quarks and charged leptons through the usual Yukawa interactions.** And the main mode is of course top and bottom quarks due to the large Yukawa coupling.

As for a process of $h_0 \rightarrow \gamma\gamma$, which has tiny background, the decay width is modified due to the charged Higgs loop contribution, which is given by

$$\Gamma(h_0 \rightarrow \gamma\gamma) = \Gamma^{SM}(h_0 \rightarrow \gamma\gamma) \left[1 - \lambda_3 \delta \left(\frac{100 \text{ GeV}}{M_{h^\pm}} \right)^2 \right]^2, \\ \simeq 0.997 \times \Gamma^{SM}(h_0 \rightarrow \gamma\gamma). \quad (3.43)$$

** We comment on the case of $m_{h_0} > 2m_{h^\pm, H_0, A_0, H_S, A_S}$, which is possible by changing the hierarchy of VEVs although it is out of our aim. Anyway, in this case, decay channels of $h_0 \rightarrow h^+ h^-, 2H_0, 2A_0, 2H_S, 2A_S$ open through the mixings among three Higgs fields, (H, H_ν, S) . Their decay widths are given by

$$\Gamma(h_0 \rightarrow h^+ h^-) = \frac{\lambda_3^2 m_{h_0}}{16\pi\lambda_1} \sqrt{1 - \frac{4m_{h^\pm}^2}{m_{h_0}^2}}, \quad \Gamma(h_0 \rightarrow H_S H_S, A_S, A_S) = \frac{\lambda_H^2 m_{h_0}}{32\pi\lambda_1} \sqrt{1 - \frac{4m_{H_S, A_S}^2}{m_{h_0}^2}}, \\ \Gamma(h_0 \rightarrow H_0 H_0) = \Gamma(h_0 \rightarrow A_0 A_0) = \frac{(\lambda_3 + \lambda_4)^2 m_{h_0}}{32\pi\lambda_1} \sqrt{1 - \frac{4m_{H_0, A_0}^2}{m_{h_0}^2}},$$

respectively.

Where $\delta = 0.16$ for 1 TeV charged Higgs[7]. Thus, in our model with TeV-scale mass of the charged Higgs, the modification of $h_0 \rightarrow \gamma\gamma$ is tiny, less than $\mathcal{O}(1)\%$.

3.4 Lepton flavor violation & anomalous magnetic moment

Let us estimate lepton flavor violating process induced from charged Higgs boson 1-loop diagrams. Remind that Yukawa interactions of neutrinos in Eq.(2.2) are given by

$$\frac{1}{2}y_{ij}^N S \bar{N}_i^c N_j + y_{ij}^\nu \bar{N}_i^c (\nu_j H_\nu^0 - l_{jL} H_\nu^+) + \text{h.c.} \quad (3.44)$$

Here we assume

$$y_{ij}^N = \frac{M_M}{\langle S \rangle} \delta_{ij}, \quad (3.45)$$

for simplicity. M_M is a mass parameter of order TeV-scale. Then, the mass matrix of the light neutrinos become

$$M_\nu = \frac{h_\nu^2}{M_M} \sum_j y_{ij}^\nu y_{ij}^\nu. \quad (3.46)$$

Noting $U y^\nu y^{\nu T} U^T = \text{diag.}(4y_1^{\nu 2}, 4y_2^{\nu 2}, 4y_3^{\nu 2})$ where U is the MNS matrix, Yukawa coupling $y_{ij}^\nu = 2y_i^\nu \delta_{ik} (U^T)_{kj}$ is given by

$$y_{ij}^\nu \simeq \begin{pmatrix} \sqrt{3}cy_1^\nu & -\frac{1}{\sqrt{2}}(1+\sqrt{3}s)y_1^\nu & \frac{1}{\sqrt{2}}(1-\sqrt{3}s)y_1^\nu \\ cy_2^\nu & \frac{1}{\sqrt{2}}(\sqrt{3}-s)y_2^\nu & -\frac{1}{\sqrt{2}}(\sqrt{3}+s)y_2^\nu \\ 2sy_3^\nu & \sqrt{2}cy_3^\nu & \sqrt{2}cy_3^\nu \end{pmatrix}. \quad (3.47)$$

Where we note $s = \sin \theta_{13}$, $c = \cos \theta_{13}$, and take $\theta_{12} = \pi/6$, $\theta_{23} = \pi/4$.

A branching ration of $l_i \rightarrow l_j \gamma$ to $l_i \rightarrow l_j \nu_i \bar{\nu}_j$ is given by[13]

$$R(l_i \rightarrow l_j \gamma) = \frac{192\pi^3 \alpha}{G_F^2 m_{l_i}^4} \left| \sum_k \frac{y_{kl_i}^\nu y_{kl_j}^\nu}{48(4\pi)^2} \frac{m_{l_i}^2}{m_{h^+}^2} \right|^2. \quad (3.48)$$

where α is the fine structure constant $\alpha = e^2/4\pi$ and m_{l_i} is the i -th generation charged lepton mass. For example, by using $Br(\mu \rightarrow e \nu \bar{\nu}) \simeq 1$, the branching ration $\mu \rightarrow e \gamma$ is given by

$$Br(\mu \rightarrow e \gamma) \simeq \frac{\alpha M_M^2}{98304\pi G_F^2 m_{h^+}^4 h_\nu^4} \cos^2 \theta (\sqrt{3}\delta m_{12} + \sin \theta (3\delta m_{12} + 4\delta m_{23}))^2, \quad (3.49)$$

$$= \frac{\pi \alpha}{384 G_F^2} \left(\frac{\alpha_{\nu_i}}{m_{h^+}^2} \right)^2 \frac{\cos^2 \theta}{m_{\nu_i}^2} (\sqrt{3}\delta m_{12} + \sin \theta (3\delta m_{12} + 4\delta m_{23}))^2, \quad (3.50)$$

where $\alpha_{\nu_i} \equiv \frac{y_{\nu_i}^2}{4\pi}$, $\theta = \theta_{13}$, m_{ν_i} is the lightest neutrino mass (which means $m_\nu = m_{\nu_1}$ in the NH and $m_\nu = m_{\nu_3}$ in the IH as will be shown in Eqs.(3.53) and (3.54)), and

$$\delta m_{ij} \equiv m_j - m_i, \quad \Delta m_{ij}^2 \equiv m_j^2 - m_i^2. \quad (3.51)$$

Generation dependence of neutrino mass, m_i , depends on neutrino mass hierarchy, NH or IH. By using neutrino oscillation experimental data[1],

$$\Delta m_{\odot}^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2, \quad \Delta m_{atm}^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2, \quad (3.52)$$

and the lightest neutrino mass, m_{ν_i} , NH shows

$$m_1 = m_{\nu}, \quad m_2 = \sqrt{m_{\nu}^2 + \Delta m_{\odot}^2}, \quad m_3 = \sqrt{m_{\nu}^2 + \Delta m_{\odot}^2 + \Delta m_{atm}^2}, \quad (3.53)$$

and IH shows

$$m_1 = \sqrt{m_{\nu}^2 - \Delta m_{\odot}^2 + \Delta m_{atm}^2}, \quad m_2 = \sqrt{m_{\nu}^2 + \Delta m_{atm}^2}, \quad m_3 = m_{\nu}, \quad (3.54)$$

respectively. In case of degenerate neutrino masses, both NH and IH become

$$Br(\mu \rightarrow e\gamma) \rightarrow \frac{\pi\alpha}{1536G_F^2} \left(\frac{\alpha_{\nu_i}}{m_{h^+}^2} \right)^2 \frac{\cos^2 \theta}{m_{\nu}^4} \left(\sqrt{3}\Delta m_{12}^2 + \sin \theta (3\Delta m_{12}^2 + 4\Delta m_{23}^2) \right)^2. \quad (3.55)$$

It means the branching ratio decreases as $m_{\nu_i}^{-4}$ in the degenerate hierarchy region which can be shown in Figures 2.

As for processes of $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$, they are given by

$$R(\tau \rightarrow \mu\gamma) = \frac{192\pi^3\alpha}{G_F^2 m_{\tau}^4} \left| \sum_k \frac{y_{k\tau}^{\nu} y_{k\mu}^{\nu}}{48(4\pi)^2} \frac{m_{\tau}^2}{m_{h^+}^2} \right|^2, \quad (3.56)$$

$$R(\tau \rightarrow e\gamma) = \frac{192\pi^3\alpha}{G_F^2 m_{\tau}^4} \left| \sum_k \frac{y_{k\tau}^{\nu} y_{ke}^{\nu}}{48(4\pi)^2} \frac{m_{\tau}^2}{m_{h^+}^2} \right|^2, \quad (3.57)$$

where

$$\sum_k y_{k\tau}^{\nu} y_{k\mu}^{\nu} = \frac{M_M}{8h_{\nu}^2} \left((\delta m_{12} - 4\delta m_{23}) - \sin^2 \theta (3\delta m_{12} + 4\delta m_{23}) \right), \quad (3.58)$$

$$\sum_k y_{k\tau}^{\nu} y_{ke}^{\nu} = -\frac{M_M \cos \theta}{4\sqrt{2}h_{\nu}^2} \left(\delta m_{12} - \sin \theta (3\delta m_{12} + 4\delta m_{23}) \right). \quad (3.59)$$

Thus, branching ratios are calculated as

$$\begin{aligned} Br(\tau \rightarrow \mu\gamma) &= Br(\tau \rightarrow \mu\nu\bar{\nu}) \frac{\pi\alpha}{768G_F^2} \left(\frac{\alpha_{\nu_i}}{m_{h^+}^2} \right)^2 \left(\frac{(\delta m_{12} + 4\delta m_{23}) - \sin^2 \theta (3\delta m_{12} + 4\delta m_{23})}{m_{\nu_i}} \right)^2, \\ &\rightarrow Br(\tau \rightarrow \mu\nu\bar{\nu}) \frac{\pi\alpha}{3072G_F^2} \left(\frac{\alpha_{\nu_i}}{m_{h^+}^2} \right)^2 \left(\frac{(\Delta m_{12}^2 + 4\Delta m_{23}^2) - \sin^2 \theta (3\Delta m_{12}^2 + 4\Delta m_{23}^2)}{m_{\nu_i}^2} \right)^2, \end{aligned} \quad (3.60)$$

$$\begin{aligned} Br(\tau \rightarrow e\gamma) &= Br(\tau \rightarrow e\nu\bar{\nu}) \frac{\pi\alpha}{384G_F^2} \left(\frac{\alpha_{\nu_i}}{m_{h^+}^2} \right)^2 \frac{\cos^2 \theta}{m_{\nu_i}^2} \left(\sqrt{3}\delta m_{12} - \sin \theta (3\delta m_{12} + 4\delta m_{23}) \right)^2 \\ &\rightarrow Br(\tau \rightarrow e\nu\bar{\nu}) \frac{\pi\alpha}{1536G_F^2} \left(\frac{\alpha_{\nu_i}}{m_{h^+}^2} \right)^2 \frac{\cos^2 \theta}{m_{\nu}^4} \left(\sqrt{3}\Delta m_{12}^2 + \sin \theta (3\Delta m_{12}^2 + 4\Delta m_{23}^2) \right)^2, \end{aligned} \quad (3.61)$$

respectively. Where the second line in each equation is degenerate neutrino mass limit, and we use $Br(\tau \rightarrow \mu\nu\bar{\nu}) \simeq 0.17$ and $Br(\tau \rightarrow e\nu\bar{\nu}) \simeq 0.18$ [14] in the following numerical calculations.

Figures 1 show θ dependence of branching ratios of $\mu \rightarrow e\gamma$ (red line), $\tau \rightarrow e\gamma$ (blue line), and $\tau \rightarrow \mu\gamma$ (green line) with $\alpha_\nu = 1/4\pi$, $m_\nu = 0.1$ eV, and $m_{h^+} = 1$ TeV. Dashed lines correspond to experimental bound[15, 16]. NH (IH) has decreasing point at $\theta \simeq 0.014$ ($\theta \simeq 0.013$) in $Br(\tau \rightarrow e\gamma)$ ($Br(\mu \rightarrow e\gamma)$), which can be understood from a cancellation in Eq.(3.61) (Eq.(3.55)).

Figures 2 are the lightest mass m_ν dependence of branching ratios of $\mu \rightarrow e\gamma$, $\tau \rightarrow e\gamma$, and $\tau \rightarrow \mu\gamma$ with $\alpha_\nu = 1/4\pi$ and $m_{h^+} = 1$ TeV. Red line shows $\theta = 0$, green line $\theta = 0.001$, blue line $\theta = 0.01$, and purple line $\theta = 0.1$. Dashed line corresponds to each experimental bound. The decreasing point in IH is also calculated from a cancellation in Eq.(3.55). When we take $\theta = 0.013$ in $Br(\mu \rightarrow e\gamma)$ with IH, a decreasing point emerges at $m_\nu \simeq 0.1$ eV, which is consistent with Figures 1.

Figures 1 and 2 show that a wide parameter region can be reached by the MEG experiment which has a sensitivity of order 10^{-13} [17].

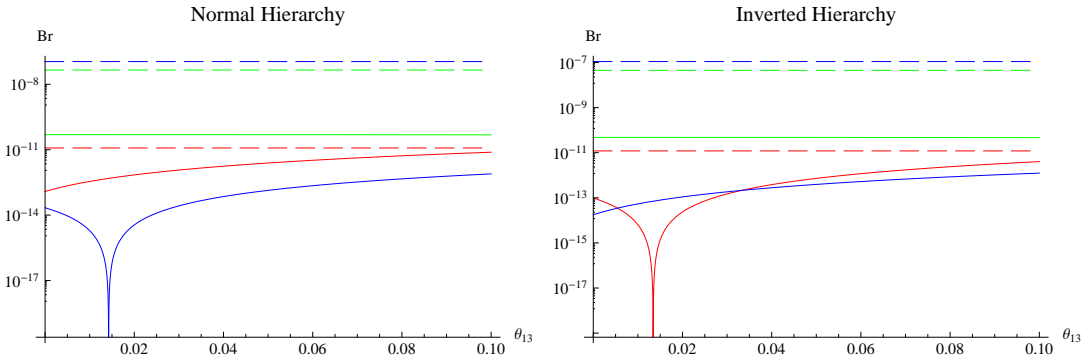


Figure 1: θ dependence of branching ratios of $\mu \rightarrow e\gamma$ (red line), $\tau \rightarrow e\gamma$ (blue line), and $\tau \rightarrow \mu\gamma$ (green line) with $\alpha_\nu = 1/4\pi$, $m_\nu = 0.1$ eV, and $m_{h^+} = 1$ TeV. Dashed lines correspond to experimental bound.

Here, let us consider a possibility that our model can generate enough large muon anomalous magnetic moment which is measured in experiments[18] as

$$\Delta a_\mu = (25.5 \pm 8.0) \times 10^{-10}. \quad (3.62)$$

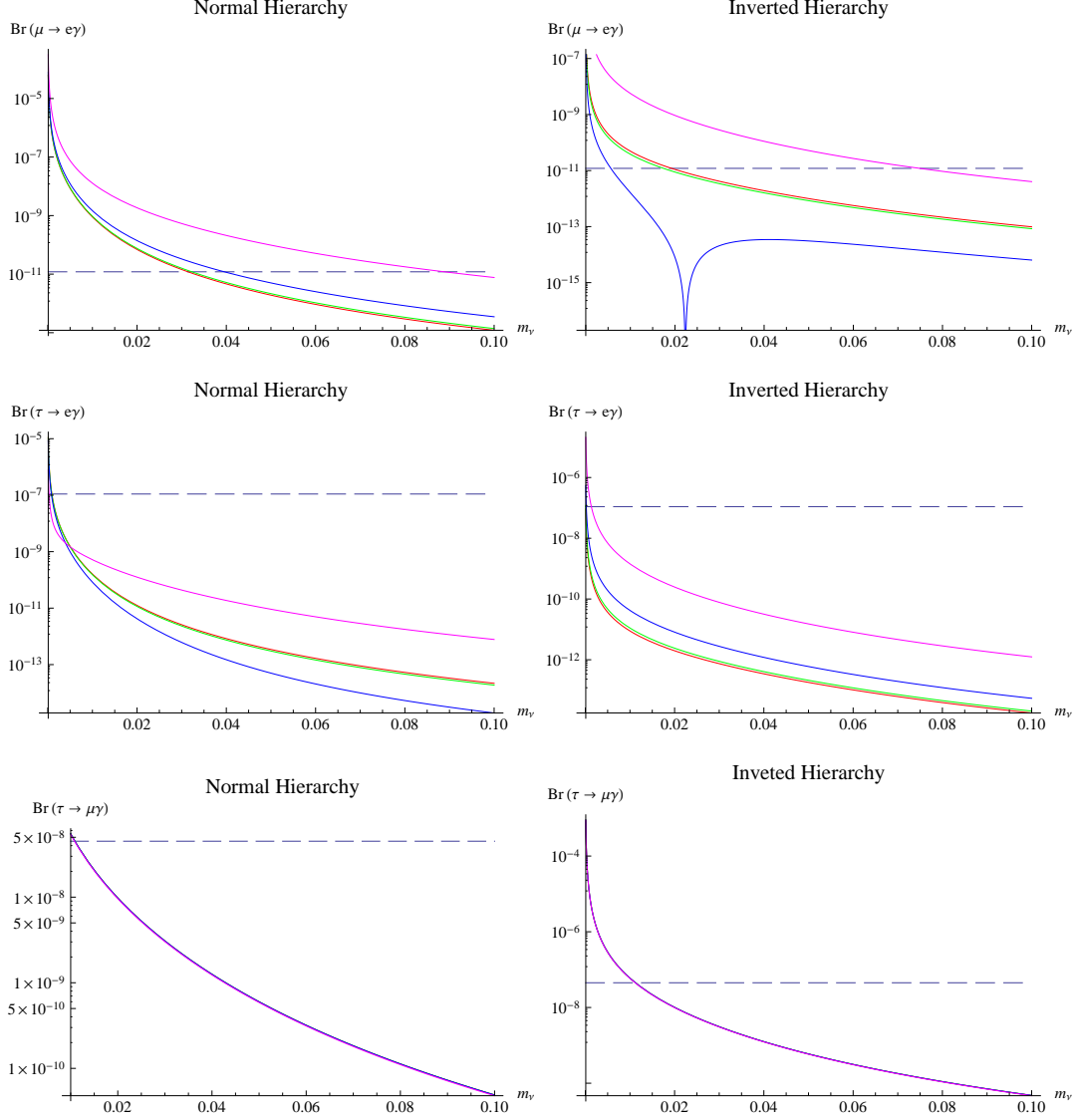


Figure 2: The lightest mass m_ν dependence of branching ratios of $\mu \rightarrow e\gamma$, $\tau \rightarrow e\gamma$, and $\tau \rightarrow \mu\gamma$ with $\alpha_\nu = 1/4\pi$ and $m_{h^+} = 1$ TeV. Red line shows $\theta = 0$, green line $\theta = 0.001$, blue line $\theta = 0.01$, and purple line $\theta = 0.1$. Dashed line corresponds to each experimental bound.

Assuming $|m_{h\pm}| \simeq |M_M|$, the muon anomalous magnetic moment is given by[13]

$$\begin{aligned}\Delta a_\mu &\simeq -\sum_i \frac{(y_{i\mu}^\nu)^2}{12(4\pi)^2} \frac{m_\mu^2}{m_{h+}^2} = \frac{\alpha_\nu m_\mu^2}{96\pi m_{h+}^2} \frac{(1 + \sqrt{3}\sin\theta_{13})^2 m_1 + (\sqrt{3} - \sin\theta_{13})^2 m_2 + 4\cos^2\theta_{13} m_3}{m_\nu} \\ &\simeq -\frac{\alpha_\nu m_\mu^2}{96\pi m_{h+}^2} \frac{m_1 + 3m_2 + 4m_3}{m_\nu},\end{aligned}\tag{3.63}$$

where we use $\theta_{12} = \pi/6, \theta_{23} = \pi/4$ ($\theta_{13} = 0$) in the first (second) line. Unfortunately, the sign is opposite from Eq.(3.62), so that our model can not induce the deviation. This situation might be changed in the supersymmetric extension[19].

3.5 Majorana nature of neutrinos

An idea of the model we suggested is similar to the model[9, 6, 7], but the biggest different point is that light active neutrinos are Majorana particles in our model. Are there experimental predictions of Majorana natures for these active neutrinos?

One is a neutrinoless double beta decay, which never occur in case of Dirac neutrinos. The phenomenological analyses in this paper used the neutrino oscillation data and $\leq \mathcal{O}(0.1)$ eV absolute mass of neutrinos from cosmology[20]. By using them, prediction about neutrinoless double beta decay is obtained. Taking vanishing Majorana CP phases, for simplicity, it is given by $\langle m_{\beta\beta} \rangle = \frac{3}{4}\cos^2\theta + \frac{1}{4}m_2\cos^2\theta + m_3\sin^2\theta$ by using $\theta_{12} = \pi/6, \theta_{23} = \pi/4$. When we take the lightest mass as 0.1 eV (0.01 eV, 0.001 eV), NH shows $\langle m_{\beta\beta} \rangle = 0.10$ eV (0.011 eV, 0.0030 eV), and IH $\langle m_{\beta\beta} \rangle = 0.11$ eV (0.049 eV, 0.048 eV), respectively.^{††} It is consistent with today's experimental bound, $\langle m_{\beta\beta} \rangle < 0.1$ eV[14].

Anyhow, above results are obtained from the current neutrino oscillation data, and they are not specific predictions from our model, TeV-scale seesaw from multi-Higgs model. Are there any direct evidences in collider experiments of our model? One of the important motivations for our model is detective new physics at TeV-scale, and it is the reason why we set TeV-scale for right-handed neutrinos.

In a high energy collider experiments, there is a chance of direct production of right-handed neutrinos. For example, in a linear collider, there are T-channel processes of charged Higgs exchange $e^+e^- \rightarrow 2N$, $e^+e^- \rightarrow 2N\gamma$, and so on. The first is missing event, and the latter is a single photon event which can be detected clearly. The decay channels of N are also interesting, since it can produce (S -originated) singlet scalars with lepton number. We will show detailed analyses in the next paper[19].

^{††} Even if we take into account of finite Majorana phases, the magnitude does not increase.

4 Summary and discussions

We have proposed a simple model for Majorana neutrino case, which is a renormalizable model with minimal extension of the SM which appears entirely below the TeV-scale. Tiny Majorana neutrino masses are obtained through a TeV-scale type I seesaw mechanism without requiring tiny Yukawa couplings. This model contains extra one Higgs singlet, and one Higgs doublet with a tiny VEV. As for extending a Higgs sector, there are constraints in general, which are consistency of electroweak precision data and absence of large FCNCs. In our model, both two constraints are satisfied since the extra doublet only has a Yukawa interaction with lepton doublets and right-handed neutrinos, and their masses are heavy enough to suppress FCNCs although its VEV is of order 0.1 eV. The extra Higgs doublet yields a neutral scalar and a neutral pseudo-scalar, and a charged Higgs particles, which can provide collider signatures. This charged Higgs can contribute to the lepton flavor violating processes. The extra singlet produces TeV-scale Majorana masses of right-handed neutrinos, and yields a neutral scalar and a neutral pseudo-scalar with a lepton number. Other phenomenology have also been represented such as the charged Higgs decay processes depending on the particle mass spectra. Notice that the decay of the charged Higgs to quarks and charged leptons are strongly suppressed due to absence of direct interactions among them, which is one of different points from usual two Higgs double models. Since active light neutrinos are Majorana particles, this model predicts a neutrinoless double beta decay.

Finally, we give a comment. The supersymmetric extension can be also achieved by introducing small magnitude of A -terms, which is expected to be induced some supersymmetry breaking scenarios. However, for the suitable gauge coupling unification we should introduce extra colored Higgs particles. In this case, we should introduce baryon number symmetry to avoid rapid proton decay.

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A Conditions of bonded below potential

We show conditions of Higgs potential to be bonded below. To obtain the conditions, we do not need to take into account mass terms and three-point interactions of Higgs fields. Thus,

we must only take the following interactions,

$$V \sim \lambda_1 h^4 + \lambda_2 h_\nu^4 + (\lambda_3 + \lambda_4) h^2 h_\nu^2 + \lambda_s s^4 + \lambda_H h^2 s^2 + \lambda_{H_\nu} h_\nu^2 s^2. \quad (\text{A.64})$$

It is rewritten as

$$\begin{aligned} V &\sim \frac{1}{2}(\lambda_1 h^4 + \lambda_2 h_\nu^4) + \frac{1}{2}(\lambda_1 h^4 + \lambda_s s^4) + \frac{1}{2}(\lambda_2 h_\nu^4 + \lambda_s s^4) + (\lambda_3 + \lambda_4) h^2 h_\nu^2 + \lambda_H h^2 s^2 + \lambda_{H_\nu} h_\nu^2 s^2, \\ &> (\sqrt{\lambda_1 \lambda_2} + \lambda_3 + \lambda_4) h^2 h_\nu^2 + (\sqrt{\lambda_1 \lambda_s} + \lambda_H) h^2 s^2 + (\sqrt{\lambda_2 \lambda_s} + \lambda_{H_\nu}) h_\nu^2 s^2, \end{aligned} \quad (\text{A.65})$$

where we use bonded below for each field's direction,

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_s > 0. \quad (\text{A.66})$$

Then, a necessary and sufficient condition of bounded below potential is that all coefficients in (A.65) are real and positive, which are given by

$$\sqrt{\lambda_1 \lambda_2} > -\lambda_3 - \lambda_4, \quad \sqrt{\lambda_1 \lambda_s} > \lambda_H, \quad \sqrt{\lambda_2 \lambda_s} > \lambda_{H_\nu}. \quad (\text{A.67})$$

Therefore, the condition of bounded below is given by Eqs.(A.66) and (A.67).

B Higgs interactions

Here, we summarize Higgs interactions below the energy scale of Higgs VEVs with an assumption of CP invariance in the Higgs sector. We denote scalars, pseudo-scalars, and charged Higgs as

$$R_i = \begin{pmatrix} H_S \\ h_0 \\ H_0 \end{pmatrix}, \quad P_i = \begin{pmatrix} A_S \\ G^0 \\ A_0 \end{pmatrix} \quad (\text{B.68})$$

· **3-points interactions of $R_i h^+ h^-$:**

Interactions are given by

$$\begin{aligned} &((2\lambda_{H_\nu} s \cos^2 \beta_3 - \mu \sin 2\beta_3 - 2\lambda_H s \sin^2 \beta_3) V_{1i} + (2\lambda_3 h \cos^2 \beta_3 + \lambda_4 h_\nu \sin 2\beta_3 + 2\lambda_1 h \sin^2 \beta_3) V_{2i} \\ &+ (2\lambda_2 h_\nu \cos^2 \beta_3 + \lambda_4 h \sin 2\beta_3 + 2\lambda_3 h_\nu \sin^2 \beta_3) V_{3i}) R_i h^+ h^- \end{aligned} \quad (\text{B.69})$$

where V_{ij} is a mixing matrix defined in Eqs.(2.22) and (2.23).

· **4-points interactions of $R_i R_j h^+ h^-$ and $P_i P_j h^+ h^-$:**

They are given by

$$\sum_{m,n} (V^\dagger)_{im} O_{mn} V_{nj} R_i R_j h^+ h^- + \sum_{m,n} (V'^\dagger)_{im} O_{mn} V'_{nj} P_i P_j h^+ h^-, \quad (\text{B.70})$$

where

$$O_{mn} = \begin{pmatrix} \lambda_{H\nu} \cos^2 \beta_\nu - \lambda_H \sin^2 \beta_3 & 0 & 0 \\ 0 & \lambda_3 \cos^2 \beta_3 + \lambda_1 \sin^2 \beta_3 & \frac{\lambda_4}{2} \sin 2\beta_3 \\ 0 & \frac{\lambda_4}{2} \sin 2\beta_3 & \lambda_2 \cos^2 \beta_3 + \lambda_3 \sin^2 \beta_3 \end{pmatrix} \quad (\text{B.71})$$

and V' is a mixing matrix for imaginary part defined in Eqs.(2.25) and (2.26).

· **4-points interactions of $h^+h^-h^+h^-$:**

They are give by

$$\left(\frac{1}{2} \lambda_1 \sin^4 \beta_3 + \frac{1}{2} \lambda_2 \cos^4 \beta_3 + (\lambda_3 + \lambda_4) \cos^2 \beta_3 \sin^2 \beta_3 \right) h^+ h^- h^+ h^-. \quad (\text{B.72})$$

· **3-points interactions of neutral Higgs:**

They are given by

$$\sum_{l,m,n} T_{lmn} V_{li} (V^\dagger)_{jm} V_{nk} R_i R_j R_k + \sum_{l,m,n} T'_{lmn} V_{li} (V'^\dagger)_{jm} V'_{nk} R_i P_j P_k, \quad (\text{B.73})$$

where T_{lmn} is a symmetric tensor as follows

$$\begin{aligned} T_{111} &= -2\lambda + 4\lambda_S s, & T_{112} &= -\frac{2}{3} \lambda_H h, & T_{113} &= \frac{2}{3} \lambda_{H\nu} h_\nu, & T_{122} &= -\frac{2}{3} \lambda_H s, & T_{123} &= -\frac{\mu}{3}, \\ T_{133} &= \frac{2}{3} \lambda_S s, & T_{222} &= 2\lambda_1 h, & T_{223} &= \frac{2}{3} (\lambda_3 + \lambda_4) h_\nu, & T_{233} &= \frac{2}{3} (\lambda_3 + \lambda_4) h, & T_{333} &= 2\lambda_2 h_\nu, \end{aligned}$$

with

$$\begin{aligned} T'_{1jk} &= \begin{pmatrix} 6\lambda + 4\lambda_S s & 0 & 0 \\ 0 & -2\lambda_H s & -\mu \\ 0 & -\mu & 2\lambda_{H\nu} s \end{pmatrix}, \\ T'_{2jk} &= \begin{pmatrix} -2\lambda_H h & 0 & \mu \\ 0 & 2\lambda_1 h & 0 \\ \mu & 0 & 2(\lambda_3 + \lambda_4) h \end{pmatrix}, \\ T'_{3jk} &= \begin{pmatrix} 2\lambda_{H\nu} h_\nu & -\mu & 0 \\ -\mu & 2(\lambda_3 + \lambda_4) h_\nu & 0 \\ 0 & 0 & 2\lambda_2 h_\nu \end{pmatrix}. \end{aligned}$$

· **4-points interactions of neutral Higgs:**

They are given by

$$\begin{aligned} & \sum_{m,n,s,t} X_{mnst} (V_{mi}^\dagger) (V_{jn}^\dagger) V_{sk} V_{tl} R_i R_j R_k R_l + \sum_{m,n,s,t} X'_{mnst} (V_{mi}^\dagger) (V_{jn}^{\prime\dagger}) V_{sk} V'_{tl} R_i P_j R_k P_l \\ & + \sum_{m,n,s,t} X_{mnst} (V_{mi}^{\prime\dagger}) (V_{jn}^{\prime\dagger}) V'_{sk} V'_{tl} P_i P_j P_k P_l, \end{aligned} \quad (\text{B.74})$$

where $X_{1111} = \lambda_S$, $X_{\sigma(1122)} = -\frac{\lambda_H}{6}$, $X_{\sigma(1133)} = \frac{\lambda_{H\nu}}{6}$, $X_{2222} = \frac{1}{2}\lambda_1$, $X_{\sigma(2233)} = \frac{1}{6}(\lambda_3 + \lambda_4)$, $X_{3333} = \frac{1}{2}\lambda_2$,

$$X'_{11st} = \begin{pmatrix} 2\lambda_S & 0 & 0 \\ 0 & -\lambda_H & 0 \\ 0 & 0 & \lambda_{H\nu} \end{pmatrix}, \quad X'_{22st} = \begin{pmatrix} -\lambda_H & 0 & 0 \\ 0 & \lambda_1 & 0 \\ 0 & 0 & \lambda_3 + \lambda_4 \end{pmatrix}$$

$$X'_{33st} = \begin{pmatrix} \lambda_{H\nu} & 0 & 0 \\ 0 & \lambda_3 + \lambda_4 & 0 \\ 0 & 0 & \lambda_2 \end{pmatrix}, \quad \text{others} = 0.$$

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